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# Measurement of the photonic de Broglie wavelength of parametric down-converted photons using a Mach-Zehnder interferometer

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We propose and demonstrate the measurement of photonic de Broglie wavelength of an entangled photon pair state (a biphoton) generated by parametric down-conversion utilizing a normal Mach-Zehnder interferometer. The observed interference manifests the concept of the photonic de Broglie wavelength.

## I. INTRODUCTION

Recently, interferometric properties of multiphoton states and their application have been attracting much attention. Jacobson *et al.* [1] proposed the concept of "photonic de Broglie wave" in multiphoton states. They argued that the photonic de Broglie wavelength of an ensemble of photons with wavelength $\lambda$ and average number of photons $N$ can be measured to be $\lambda/N$ using a special interferometer with "effective beam splitters" that do not split the multiphoton states into constituent photons. Fonseca *et al.* [2] measured the photonic de Broglie wavelength of a two-photon state using a kind of Young's double slit interferometer. Boto *et al.* [3] proposed the principle of "quantum lithography", utilizing reduced interferometric diffraction of non-classical $N$ photon states. Very recently, a proof-of-principle experiment of the quantum lithography was demonstrated [4].

We propose and demonstrate the measurement of photonic de Broglie wavelength for $N$=2 in a very simple and straightforward manner, utilizing entangled photon pairs ("biphotons") generated by parametric down-conversion and a normal Mach-Zehnder (M-Z) interferometer. We discuss the nature of the biphoton interference, which is essentially governed by the frequency correlation between constituent two photons.

## II. EXPERIMENT

Figure 1 shows the schematic view of our experimental setup. Pairs of entangled photons were generated by spontaneous parametric down-conversion (SPDC) in a 5 mm long $KNbO_3$ (KN) crystal, pumped by the second harmonic light of a single longitudinal mode Ti:sapphire laser (linewidth $\Delta\nu_0 \sim 40$ MHz) operating at $\lambda_0$=861.6 nm. We selected degenerate photon pairs, each wavelength of which was centered at $\lambda_0$, using two pinholes after the SPDC. The M-Z interferometer are composed of two 50/50% beamsplitters (BS1 and BS2). Biphotons were generated at either arm of the interferometer when a pair of down-converted photons simultaneously entered at both input ports of a beam splitter (BS1), as a result of Hong-Ou-Mandel (HOM) interference [5]. The path-length difference between the two arms of the M-Z interferometer was controlled by a piezoelectric positioner. The two paths are combined together at the output beamsplitter (BS2), and the biphoton interference was measured at one of the output ports of BS2. The biphoton interference pattern was recorded by a two-photon detector, consisting of a 50/50% beam splitter (BS3) and two avalanche photodiodes (APD) followed by a coincidence counter. In front of each APD, we put an interference filter (center wavelength $\lambda_c$ = 860 nm, bandwidth $\Delta\lambda$ = 10 nm). As a whole, the interferometer was designed to measure the photonic de Broglie wavelength of the biphoton without using any special "effective beam splitters". For comparison, we also measured the usual one-photon interference using a single detector and blocking one of the input ports.

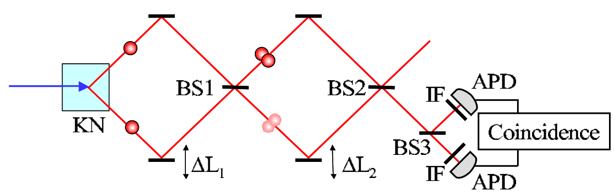


FIG. 1: Schematic experimental setup of the biphoton interference. KN: $KNbO_3$ crystal, BS1~3: beam splitters, IF: interference filters, APD: avalanche photodiodes.

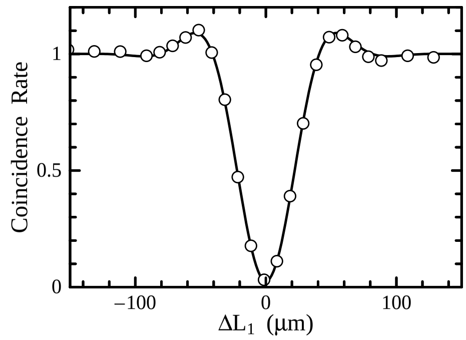


FIG. 2: Coincidence counting rate detecting the photons after the two output ports of BS1 as a function of the optical path-length difference ($\Delta L_1$) between the two paths from KN and BS1 in Fig. 1.

It is worth discussing interference patterns expected in our experiment. For simplicity, we consider only single frequency (monochromatic) photons. The monochromatic treatment is adequate to predict the most distinct properties of the interference patterns, although spectral distribution should be considered to discuss more detailed phenomena such as coherent length of the interference. The one and two-photon counting rates ($R_5$ and $R_{55}$, respectively) at one of the output ports of the interferometer are

$$R_5 \propto \langle \psi_0, \psi_1 | a_5^\dagger a_5 | \psi_0, \psi_1 \rangle, \quad (1)$$

$$R_{55} \propto \langle \psi_0, \psi_1 | a_5^\dagger a_5^\dagger a_5 a_5 | \psi_0, \psi_1 \rangle, \quad (2)$$

where $a_5^\dagger$ and $a_5$ are photon creation and annihilation operators at the output port, $\psi_0$ and $\psi_1$ denote the quantum states of the two input ports. The photon operators at the output ports are connected to those of the input ports through the scattering matrices of the beamsplitters and the optical path-length difference [6]. Thus we can calculate the counting rates (1) and (2) for arbitrary input states of light. The resultant two-photon interference pattern for the case $|\psi_0, \psi_1\rangle = |1, 1\rangle$, i.e., both inputs are $N{=}1$ Fock states, is

$$R_{55} \propto 1 - \cos 2\phi, \quad (3)$$

where $\phi{=}2\pi\Delta L_2/\lambda$ is the optical phase difference in the two arms, $\Delta L_2$ the path-length difference, and $\lambda$ the wavelength of the input light. The corresponding one-photon interference for the case $|\psi_0, \psi_1\rangle = |0, 1\rangle$ is

$$R_5 \propto 1 - \cos \phi. \quad (4)$$

From Eqs. (3) and (4), we see that $R_{55}$ will have the oscillation period $\lambda/2$, while $R_5$ has the period $\lambda$. This oscillation period $\lambda/2$ for the two-photon counting rate $R_{55}$ is attributable to the photonic de Broglie wavelength $\lambda/N$ for the biphoton ($N{=}2$) state.

## III. RESUTS AND DISCUSSION

The HOM interference, i.e., coincidence counting rate detecting the photons after the two output ports of BS1 as a function of the optical path-length difference ($\Delta L_1$) between the two input ports, is presented in Fig. 2. The visibility of the HOM interference was 0.97, guaranteeing that the photon pair was almost perfectly traveling together along either arm of the interferometer at $\Delta L_1{=}0$. Figure 3 shows the measured interference pattern for both one-photon (upper graph) and two-photon (lower graph) detection, as a function of path-length difference ($\Delta L_2$) between the two arms of the interferometer, around $\Delta L_2{\sim}0$ $\mu$m. Note that one of the input ports of the interferometer was blocked when measuring the one-photon counting rate, otherwise no interference is expected. One can see that the interference patterns for the one- and two-photon counting rates are well reproduced by Eqs. (4) and (3), respectively, and that the interference in the one-photon counting rate has a period of approximately 860 nm, whereas the interference period in the two-photon counting rate is approximately 430 nm. This result clearly indicates that the biphoton state exhibits the interference as a "wave" with half wavelength of the one-photon state. Thus, we have observed the photonic de Broglie wavelength of the biphoton state.

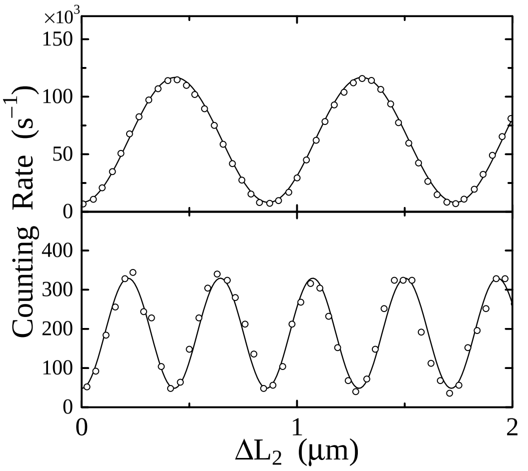


FIG. 3: Interference patterns in the one-photon (upper) and two-photon (lower) counting rates at path-length difference around 0 $\mu$m.

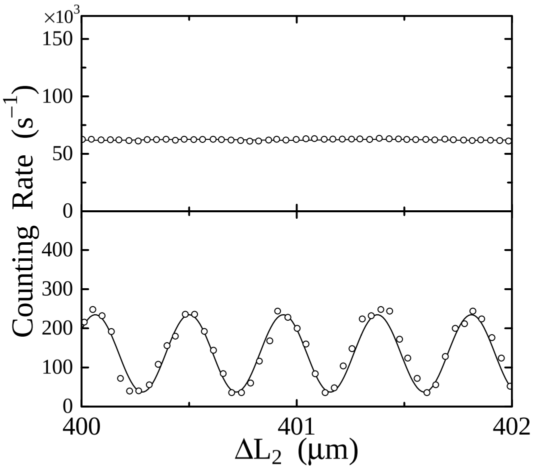


FIG. 4: Interference patterns in the one-photon (upper) and two-photon (lower) counting rates at path-length difference around 400 $\mu$m.

Furthermore, we have also observed the difference of the coherence length between the one- and two-photon counting rates as demonstrated in Fig. 4. Although the oscillational interference in the one-photon counting rate disappear at $\Delta L_2{\sim}400$ $\mu$m, the interference of the two-photon counting rate still remains for much larger path-length difference, indicating that biphotons have much longer coherence length than the single photons. Since the spontaneous parametric down-converted photons have considerably wide spectral width, the coherence length of the single-photon counting rate is governed by the spectral bandwidth $\Delta\lambda$ of the interference filters placed in front of the detectors. Thus, the coherence length of the single-photon counting rate becomes very short ($\lambda_c^2/\Delta\lambda \sim 70\ \mu$m). On the other hand, the coherence length of the two-photon counting rate is governed by the spectral width of the sum frequency of signal ($\nu_s$) and idler ($\nu_i$) photons, that is identical to the frequency of pump photons ($2\nu_0$) of the parametric down conversion. Since we used the second harmonic of the single longitudinal mode continuous laser as the pump source, its coherence length is very long ($c/\Delta\nu_0 \sim 400$ cm). As a result, clear interference fringe was observed for the two-photon counting rate even at $\Delta L_2 \sim 400\ \mu$m, whereas almost no fringe was observed for the one-photon counting rate. This is the direct consequence of the frequency correlation:

$$\nu_s + \nu_i = 2\nu_0 \tag{5}$$

between the constituent signal and idler photons of the biphoton. Thus, the fringe interval and coherence length of the two-photon counting rate consistently indicate that the biphoton is associated with the photonic de Broglie wavelength:

$$\lambda_b = \frac{c}{\nu_s + \nu_i} = \frac{c}{2\nu_0} = \frac{\lambda_0}{2}, \tag{6}$$

where refractive index dispersion is neglected.

So far, there have been a number of works concerning two-photon interference using parametric down-converted photons and a Mach-Zehnder or Michelson interferometer [7, 8, 9, 10]. However, the previous experiments did not intend to observe the photonic de Broglie wave. Most of these experiments [7, 8, 10] detected two photons at both output ports of the interferometer. In our experiment, by detecting the two-photon counting rate at one of the output ports, we directly showed that the observed biphoton interference manifests the concept of photonic de Broglie wavelength. Finally, we note the relationship between our experiment and the non-local nature of the correlated two photons, i.e., biphotons, generated by parametric down-conversion or atomic cascade fluorescence. As previously proposed [11] and demonstrated [12, 13], two-photon quantum interference occurs for biphotons even using two spatially separated interferometers. Thus, we understand that the interferometric properties of the biphoton originate from its non-local quantum correlation between the constituent photons, but not from the spatial closeness of the two photons.

In conclusion, we have successfully measured the photonic de Broglie wavelength of the biphotons generated by parametric down-conversion utilizing a Mach-Zehnder interferometer, and showed that the nature of biphoton interference is essentially governed by the frequency correlation between the constituent two photons.

**Acknowledgments**

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[1] J. Jacobson, G. Bjork, I. Chuang, and Y. Yamamoto, Phys. Rev. Lett. 74, 4835 (1995).
[2] E.J.S. Fonseca, C.H. Monken, and S. Pauda, Phys. Rev. Lett. 82, 2868 (1999); E.J.S. Fonseca, C.H. Monken, S. Pauda, and G.A. Barbosa, Phys. Rev. A 59, 1608 (1999).
[3] A.N. Boto, P. Kok, D.S. Abrams, S.L. Braunstein, C.P. Williams, and J.P. Dowing, Phys. Rev. Lett. 85, 2733 (2000).
[4] M. D'Angelo, M.V. Chekhova, and Y. Shih, Phys. Rev. Lett. 87, 013602 (2001).
[5] C.K. Hong, Z.Y. Ou, and L. Mandel, Phys. Rev. Lett. 59, 2044 (1987).
[6] *e.g.* L. Mandel and E Wolf, *Optical Coherence and Quantum Optics* (Campridge University Press, 1995), Sec. 12.12.
[7] J.G. Rarity, et al., Phys. Rev. Lett. 65, 1348 (1990).
[8] Z.Y. Ou, X.Y. Zou, L.J. Wang, and L. Mandel, Phys. Rev. A 42, 2957 (1990).
[9] J. Brendel, E. Mohler, and W. Martienssen, Phys. Rev. Lett. 66, 1142 (1991).
[10] Y.H. Shih, et al., Phys. Rev. A 49, 4243 (1994).
[11] J.D. Franson, Phys. Rev. Lett. 62, 2205 (1989).
[12] Z.Y. Ou, X.Y. Zou, L.J. Wang, and L. Mandel, Phys. Rev. Lett 65, 321 (1990).
[13] P.G. Kwiat, A.M. Steinberg, and R.Y. Chiao, Phys. Rev. A 47, R2472 (1993).